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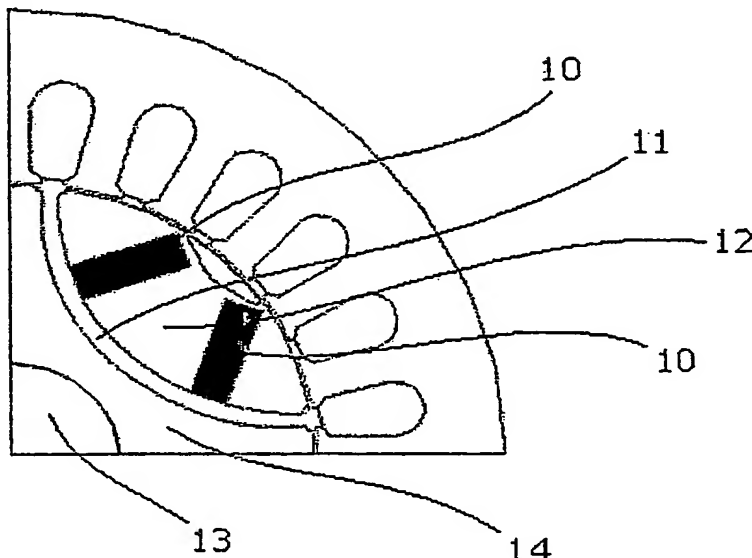
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(54) Title: SYNCHRONOUS MOTOR WITH PERMANENT MAGNET ROTOR



(57) Abstract: Permanent magnet  
synchronous motor with modified rotor  
to obtain saliency ratio  $L_d/L_q$  higher than  
one, hereinafter referred to as NSPM motor  
(Normal Saliency PM motor).

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# SYNCHRONOUS MOTOR WITH PERMANENT MAGNET ROTOR

## DESCRIPTION

### Technical field

This invention pertains to the motor field and in particular to the permanent magnet motors.

### Overview on the technique

With reference to the permanent magnet synchronous motors, motors with permanent magnet placed on the inside of the rotary part, so-called rotor, are very important. These motors are called by the initials IPM, acronym for Interior Permanent Magnet.

IPM synchronous motors offer many advantages from the mechanical, geometrical, magnetic and performance point of view.

Indeed, from the mechanical point of view, they allow the use of simpler magnets whose housing inside the rotor body can be made without using any gluing and bandaging materials, otherwise usually utilized with not inner permanent magnet motors. The total resulting geometry is thus more compact and robust, allowing higher operating speed. From the magnetic point of view, the permanent magnet results more protected against motor overloads, being less exposed to demagnetizations. To end, from the performance point of view, there are many advantages: first of all the total efficiency is higher, since rotor losses are near zero; then the presence of a further reluctance torque, in addition to that due to the permanent magnet, allows higher torque-to-volume values to be reached and to maintain high performances both at high and slow speed operation. This entails the possibility to obtain high accelerating values, more compact dimensions – implying fewer inertia and accordingly greater speed control flexibility – and high flux-weakening speed functioning.

IPM motors have two main magnetic flux axes, one so-called *direct* axis corresponding to the flux produced by the permanent magnet, one so-called *quadrature* axis at 90 electric degrees to the direct axis. The direct axis coincides with the polar axis, whereas the quadrature axis coincides with the interpolar axis. Thus, these axes are fixed onto the rotor geometry base. A major role is played by the stator direct (d\_axis) and stator quadrature (q\_axis) inductances. The latter are defined as a ratio

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between the flux linkage with the stator winding and the stator currents that produces the said flux linkage, when such fluxes are respectively centred with the direct and quadrature axes. By  $L_d$  is indicated the direct inductance and by  $L_q$  the quadrature inductance. The difference between the two inductances is responsible for the reluctance torque. A parameter estimation of the above inductances is represented by the so-called *saliency ratio* described as the ratio between the direct axis inductance ( $L_d$ ) and the quadrature axis inductance ( $L_q$ ). The resulting value is lower than one for IPM motors, thus these motors are defined with an inverse saliency PM motors (in comparison to conventional wound field synchronous motors that present  $L_d$  greater than  $L_q$ ).

From the construction point of view, the stator of IPM motors results similar to that of induction motors, whereas the rotor may have different configurations depending on how the permanent magnet is fixed. Generally, two categories are highlighted: magnet rotors with tangential magnetization and magnet rotors with radial magnetization.

It is understandable the interest in improving the overall performances of IPM motors in order to make them even more suitable in the different fields of application such as, by way of an example, light electric traction and spindle functioning of machine tools.

### Disclosure of the invention

The herein illustrated invention allows to create IPM motors exhibiting higher performances compared to the conventional motors. This is attained by reducing the quadrature inductance value ( $L_q$ ) and increasing the direct inductance value ( $L_d$ ) so that the saliency ratio  $L_d/L_q$  is higher than one. For this reason the above said motors are hereinafter referred to as NSPM motors: Normal Saliency PM motors.

Such a motor is less affected to magnetic saturation, guarantees higher performances in terms of delivered torque (rated and under overload conditions), and it offers a better behaviour to flux-weakening applications.

Furthermore, the motor of the herein illustrated invention has a lower dependence on iron saturation phenomena such to bear higher current levels.

According to the herein illustrated invention, the motor has flux barriers in the rotor lamination stack able to obstruct the magnetic flux in quadrature - so as to decrease the value of the corresponding quadrature inductance  $L_q$  -, and flux paths (flux channel) to support the direct flux, being this latter supplied either by the permanent magnets or by the stator currents - so as to increase the value of the corresponding direct inductance  $L_d$  and, consequently, increase the saliency ratio.

The above said flux barriers are made of engravings on the rotor lamination stack, arranged transversally to the flux lines to be obstructed, that is transversally to the flux lines in quadrature.

The said engravings affect the rotor lamination stack structure by creating flux channels representing a magnetic path with low reluctance for the flux of the direct axis produced by the stator currents. The presence of flux barriers and flux channels, as above illustrated, allows to obtain a saliency ratio higher than one (or normal), thus optimizing the performances of the motor in terms of:

- Greater torque for given electric load,
- Higher suitability to overload operation (possibility to operate with higher current levels without core saturation),
- Wider range of speed for operations in flux-weakening conditions,
- Lower nominal current levels for given flux-weakening speed range,
- Reduced dimensions for equal nominal torque.

As specified above, the engravings – having to obstruct the flux lines in quadrature – will be created according to the map of the flux lines due to the arrangement and dimensions of the magnets in the rotor lamellar packet.

The above said engravings are created by pressing or punching the rotor lamination stack as appropriate.

To give solidity to the structure the engravings may be interrupted by iron bridges of reduced thickness. Alternatively, holes may be punched in the flux channels so as to allow the use of braces, functioning solely for mechanical purposes.

To provide an example of a motor created applying this invention, figures 1 and 2 show two different engravings which allow the aimed target to be obtained.

Figure 1 shows that the engravings (11) have a semicircular shape and are arranged externally to the permanent magnets (10); these engravings (11) allow to obtain two flux paths. The first path (12) originates from the flux due to the permanent magnets, in the farthest part from the rotor shaft (13); the second path (14) corresponds to a magnetic channel centred on the direct axis, solely for the flow of the direct axis flux produced by the stator currents. The engravings (11) channel the direct axis fluxes, due to the permanent magnets and to the stator current, and avoid magnetic short circuit of the flux due to the permanent magnet. The flux axis in quadrature produced by the stator currents is obstructed, with a consequent increase of the saliency ratio.

In the second topology, shown in figure 2, the semicircular engravings (11) are, on the contrary, created externally to the permanent magnets (10); besides, additional radial engravings (11') are arranged to the sides of the magnets (10) so as to obtain two more distinct flux paths.

In this case, the first path (14) is that of the flux due to the permanent magnets, in the nearest part to the rotor shaft (13), the second path (15) corresponds to a magnetic channel, arranged externally to the semicircular engraving (11), solely for the flow of the direct axis flux produced by the stator currents.

Figure 3 shows the magnetic flux lines internally to the rotor created by applying the structure described in figure 1. Particularly, figure 3-a shows the map of the flux lines generated by the permanent magnets, figure 3-b shows the map of the direct axis flux lines converging inward to the channel, and figure 3-c shows the map of the quadrature axis flux lines resulting effectively obstructed by the barriers.

To evaluate the performances of the motors created applying this invention, three different profiles of power in flux-weakening condition are chosen and compared.

The change of the rotor lamination stack by applying the herein presented invention allows to create saliency values greater than one. The graphics of figure 4, in the left column, show torque values ( $t$ ) as a function of the angular speed ( $\omega$ ) of the rotor at the varying of the power ( $p$ ) delivered by the motor, whereas the right column shows the power values ( $p$ ) versus the angular speed ( $\omega$ ) of the rotor in the same conditions. Comparing the IPM motors and NSPM motors applying this invention, it is possible to quantify the performance improvement introduced by the latter motors.

Table 1 shows the values of the flux linkage ( $\Lambda_m$ ), the direct axis inductance ( $L_d$ ), the quadrature axis inductance ( $L_q$ ) and the saliency values ( $\chi = L_d/L_q$ ) of the three motors compared above, in which, by the letter (a) it is indicated a normal IPM motor, by the letter (b) it is indicated an NSPM motor with a single flux barrier obstructing the flux of the axis in quadrature and by the letter (c) it is indicated an NSPM motor with multiple flux barriers obstructing the flux of the axis in quadrature.

On the other hand, figure 5 allows to estimate the performance improvements of the NSPM motor by applying this invention in terms of torque, whereas figure 6 allows to estimate the improvements introduced by the motor by applying this invention in terms of produced power as a function of the angular speed.

#### Brief description of the drawings

- Fig. 1: Detail of the rotor of the NSPM motor applying the herein illustrated invention.
- Fig. 2: Detail of the rotor of the NSPM motor applying the herein illustrated invention.
- Fig. 3: Behaviour of the flux lines in the NSPM core motor applying the herein illustrated invention.

- Fig. 4: Graphics illustrating the behaviour of the torque and of the power supplied by the motor applying the herein illustrated invention.
- Fig. 5: Graphics illustrating the torque behaviour supplied by the motor applying the herein illustrated invention, compared with the state of the art.
- Fig. 6: Graphics illustrating the behaviour of the power supplied by the motor applying the herein illustrated invention, compared with state of the art.

### CLAIMS

1. Permanent magnet motors where the saliency ratio value is higher than one.
2. Motors as per claim in point 1 above, where the above said saliency ratio value higher than one is obtained by reducing the quadrature inductance value ( $L_q$ ).
3. Motor as per claims in points 1 and 2 above, where the rotor lamination stack has flux barriers able to obstruct the magnetic flux in quadrature, leaving undisturbed the direct flux.
4. Motor as per claims in points from 1 to 3 above, where the said barriers are made of engravings (Figure 1 and 2, 11) on the rotor lamination stack.
5. Motor as per claim in point 4 above, where the said engravings (Figure 1 and 2, 11) are made by pressing or punching the lamination stack.
6. Motor as per claims in points from 1 to 5 above, where the engravings (Figure 1, 11) form a semicircular flux path and are arranged externally to the permanent magnets (Figure 1, 10).
7. Motor as per claims in points from 1 to 5 above, where the engravings (Figure 2, 11) have a semicircular shape and are present on the outward side of the permanent magnets (Figure 2, 10) whereas radial engravings (Figure 2, 11') are present by the sides of the said magnets.



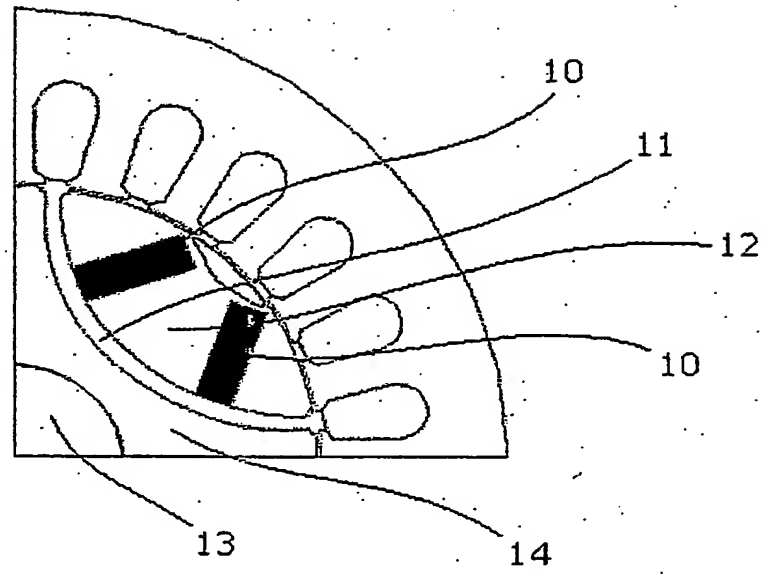


Fig. 1

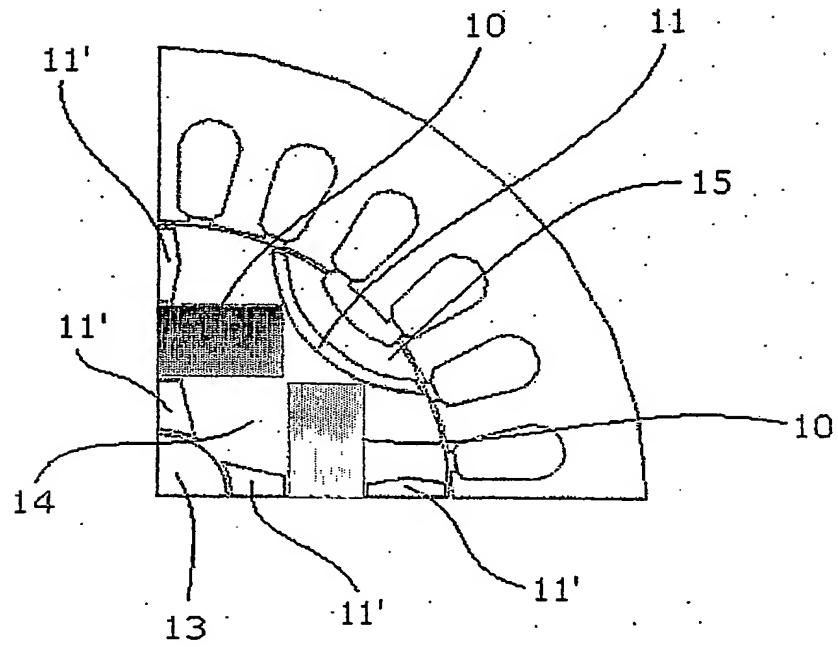
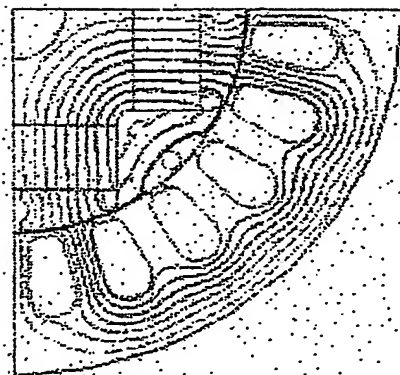
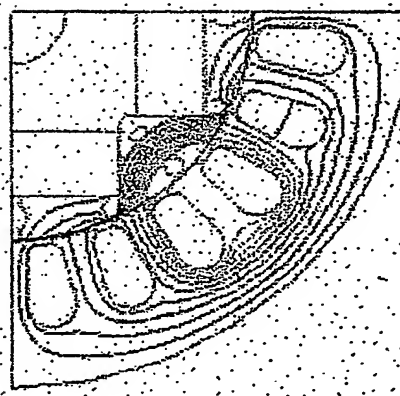


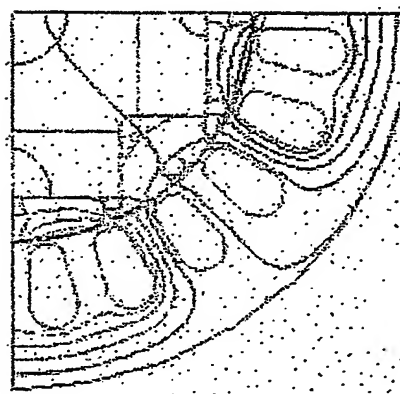
Fig. 2



a)



b)



c)

Fig. 3

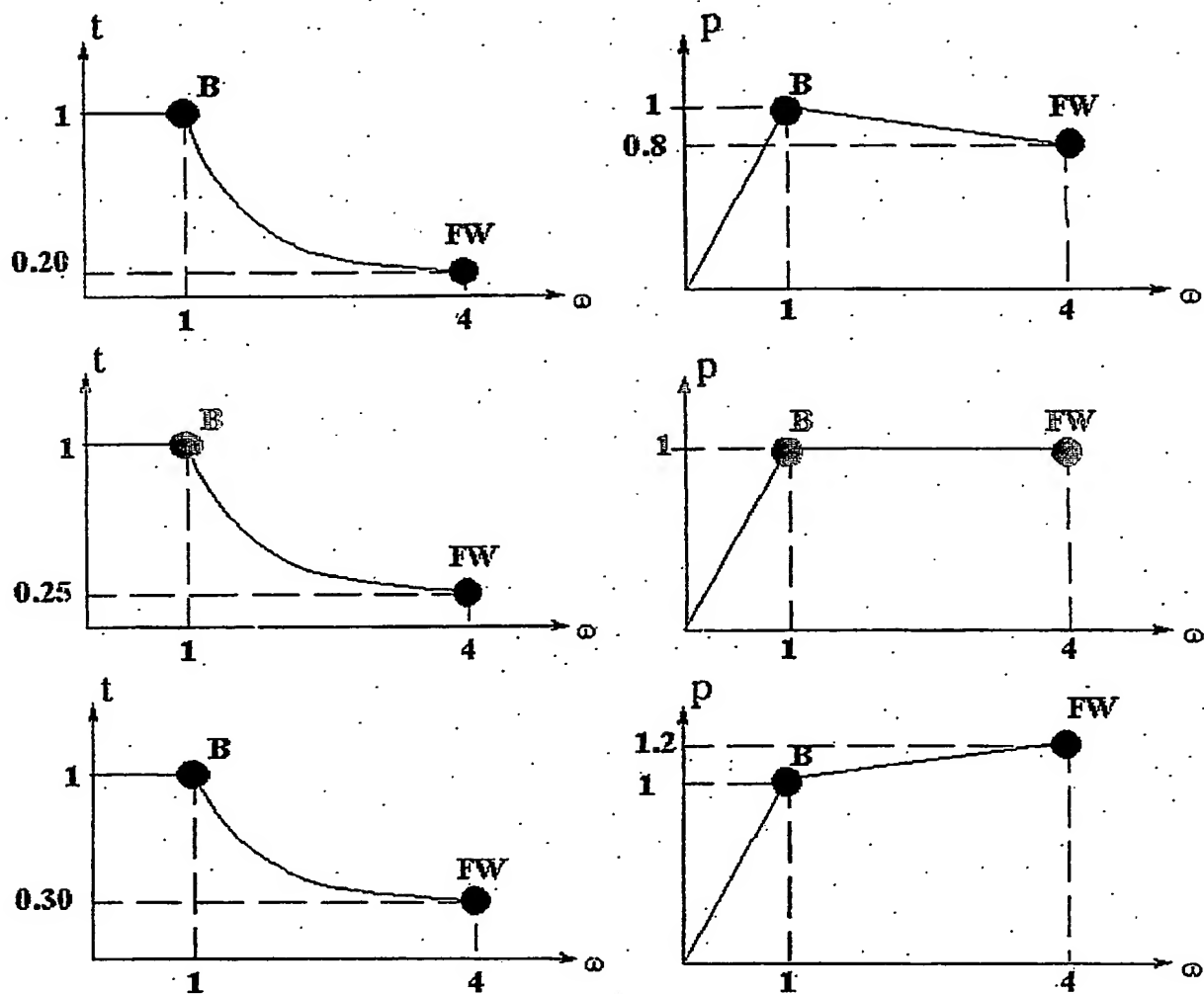


Fig. 4

Description	U.M.	(a)	(b)	(c)
Flux Linkage	$\Lambda_m$ , (mVs)	74.19	74.35	74.12
Direct Axis Inductance	$L_d$ , (mH)	0.444	0.443	0.437
Quadrature Axis Inductance	$L_q$ , (mH)	0.623	0.338	0.292
Saliency Ratio Values	$\chi = L_d/L_q$	0.71	1.31	1.50

Table 1

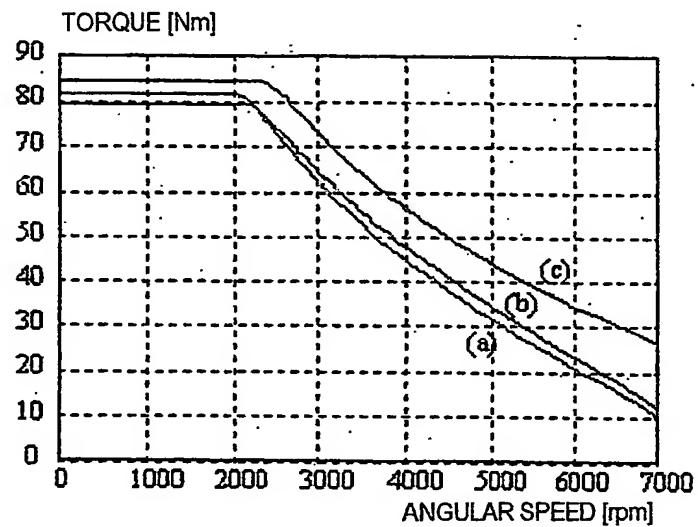


Fig. 5

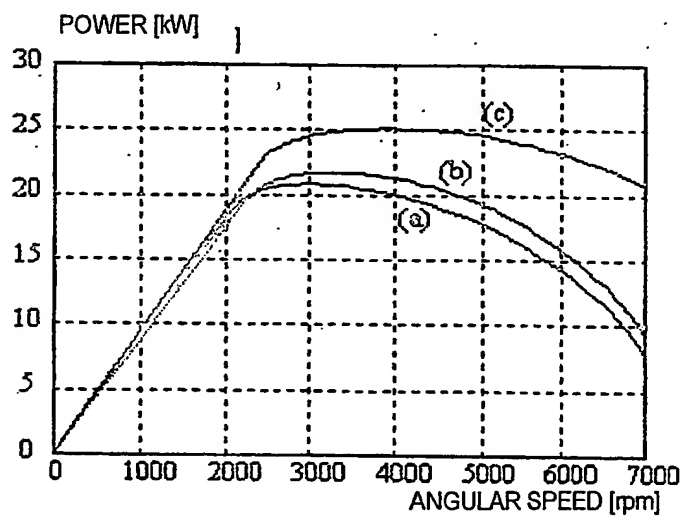


Fig. 6

# INTERNATIONAL SEARCH REPORT

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A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 H02K1/27

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	BIANCHI N ET AL: "Design considerations for a PM synchronous motor with rotor saliency for high speed drives", INDUSTRY APPLICATIONS CONFERENCE, 1999. THIRTY-FOURTH IAS ANNUAL MEETING. CONFERENCE RECORD OF THE 1999 IEEE PHOENIX, AZ, USA 3-7 OCT. 1999, PISCATAWAY, NJ, USA, IEEE, US, PAGE(S) 117-124 XP010355243	1-5
Y	ISBN: 0-7803-5589-X the whole document ----- -/--	6,7

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
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X	BIANCHI N ET AL: "SALIENT-ROTOR PM SYNCHRONOUS MOTORS FOR AN EXTENDED FLUX-WEAKENING OPERATION RANGE" 2000 , IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, IEEE INC. NEW YORK, US, VOL. 36, NR. 4, PAGE(S) 1118-1125 XP001099914 ISSN: 0093-9994 the whole document	1-5
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